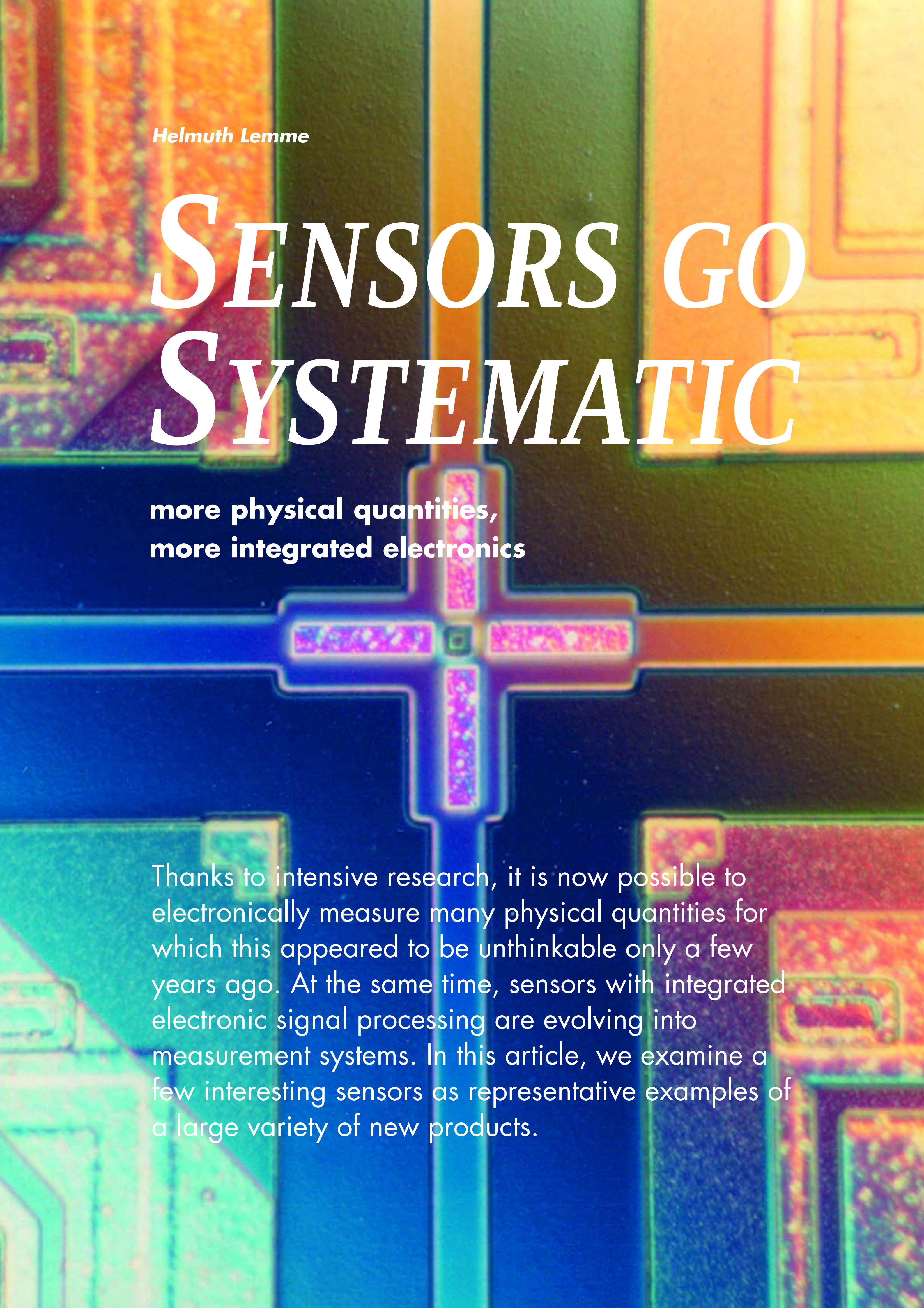

Helmuth Lemme

SENSORS GO SYSTEMATIC

more physical quantities, more integrated electronics

Thanks to intensive research, it is now possible to electronically measure many physical quantities for which this appeared to be unthinkable only a few years ago. At the same time, sensors with integrated electronic signal processing are evolving into measurement systems. In this article, we examine a few interesting sensors as representative examples of a large variety of new products.

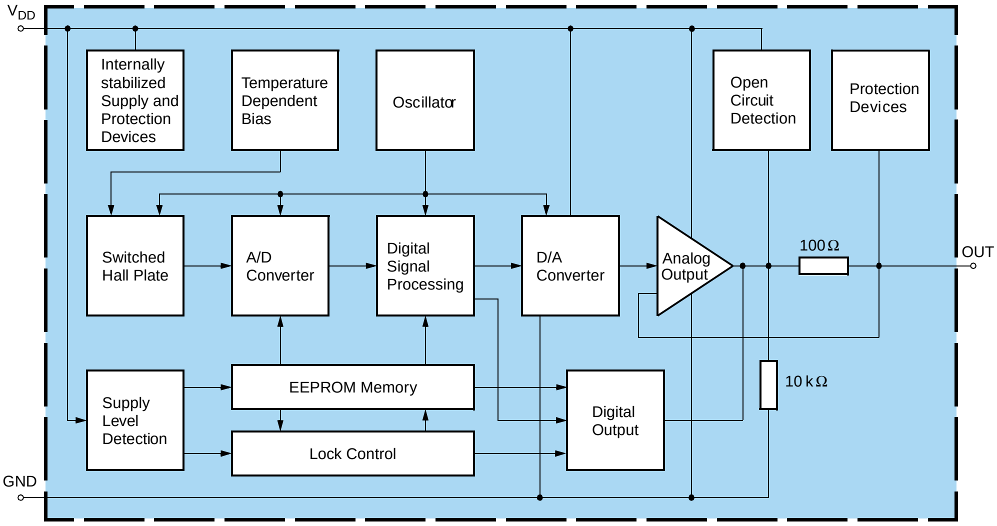

Figure 1. Block diagram of the HAL805 Hall sensor. The measurement parameters are configurable. (Micronas)

Under the increasing time and cost pressures imposed on developing instrumentation devices, building preamplifiers for sensors is increasingly coming to be seen as an irksome secondary task. They must be exactly matched to the sensor output signals, which are usually weak, and if a different type of sensor is used, the entire job has to be done all over again.

A far more user-friendly approach is to employ sensors whose signals have been preconditioned to remove distortion factors (such as temperature dependence, offsets and the like) and give them a standardised output format, such as 0–10V or 4–20 mA. This makes it easy to swap sensors.

Fitting the sensor components and measurement electronics into the same package has been common practice for a long time already. In order to further reduce costs, the present trend is increasingly heading in the direction of integrating both of these elements onto a single silicon chip. This requires finding ways to construct the actual sensor element in silicon. In many cases, this has already been successfully accomplished. For temperature sensors, it is especially easy. For pressure sensors, in which the membrane often already consists of a silicon structure bearing piezoresistive tracks, the solution is also simple. Even if such a sensor system may appear to be expensive at first glance, overall costs are reduced thanks to savings realised in development effort.

Another reason for integration is failure prevention. Human lives can depend on the reliable operation of sensors, such as in the case of ABS and ESP systems in cars. In the automotive area, a special challenge is provided by the extreme range of temperature variations, which extends from below –20 °C to the engine temperature of +125 °C. As has been shown by experience, failures of soldered joints are much more common than internal failures of ICs. Efforts to achieve increased levels of integration are thus primarily driven by considerations of safety and security.

The cost savings that arise at the same time (assuming large-scale mass production) are a welcome side effect. Another benefit is increased interference immunity. If sensor signals must pass through long cables before they are amplified, as was the case in the past, interference will be coupled in. With everything on the same chip, this hazard is eliminated.

Signal conditioning

Amplifying the signal is not the only task of signal conditioning. Many of the physical effects utilised for sensors are temperature dependent. To compensate for this, a temperature sensor that suitably adjusts the gain can be incorporated into the system. In many cases, the transfer characteristics are non-linear and must be linearised. This is especially true for conventional temperature sensors, such as NTC and platinum resistors, as well as thermocouples.

Regardless of whether linearisation is performed using conventional analogue electronics or software in the signal evaluation computer, it always requires additional effort and expense. If a silicon-based temperature sensor is available, it can be housed on the same chip and the linearisation can be implemented directly adjacent to the sensor. Such components are now in widespread use. One example is the National Semiconductor LM35, which has been manufactured for many years already. It generates an output signal that precisely and linearly increases with temperature at the rate of 10 mV/K. Over the years, it has been joined by a whole group of relatives that operate in similar manner (for more information, see www.national.com/appinfo/tempsensors/products.html).

Sensor/controller combos

Once a sensor has already become an IC, the next step is to integrate functions that were previously wired externally in the form of ‘discrete’ circuits. An example of such functions is comparators driving outputs that switch if the temperature crosses a certain threshold temperature. The threshold values can be provided externally in analogue or digital form. Integrated A/D converters are also commonly present, usually with serial output in order to save pins. The next logical step is to add a microcontroller to the chip. This makes a multitude of additional functions possible, including externally programmable parameters such as sensitivity and measurement range, calibration, and many others. An EEPROM (also on the chip) can store the calibration data. In this way, the sensor is transformed into a miniature computer.

A significant advantage of such ‘intelligent’ sensors is reduced type diversity. Instead of making a large variety of types that differ only in their detailed specifications, manufacturers can make just a few basic types, which can then be produced in much larger quantities. The parameters required for operational use are entered by the user, and in many cases they can also be subsequently modified.

A typical example of this type of sensor is the family of Hall sensors made by Micronas. The first model of this family was the HAL800, which was further refined to yield the derivative types HAL805, HAL810 and HAL815 (www.micronas.com/products/overview/sensors/index.php).

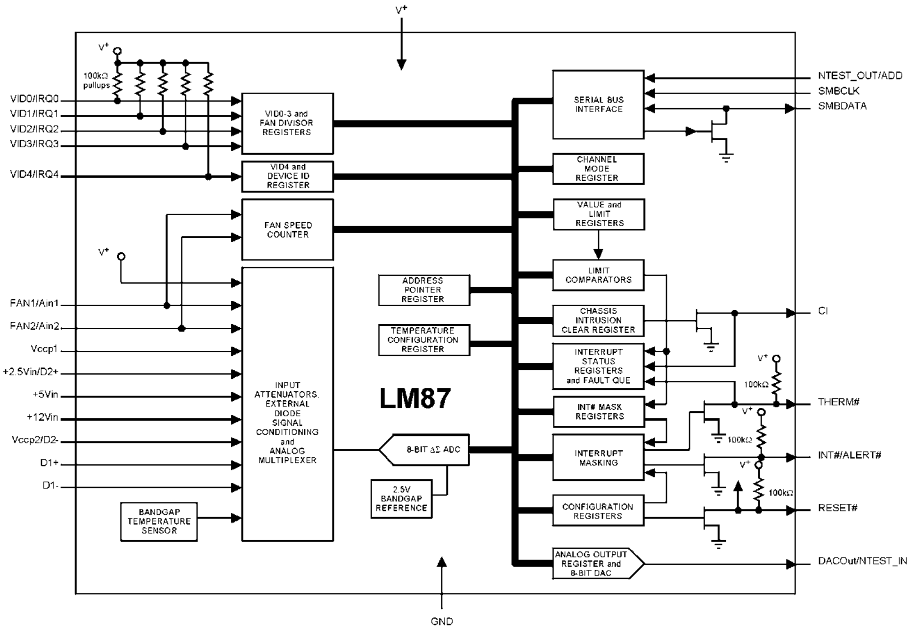

Figure 2. Block diagram of the LM87 supervisory IC. The temperature sensor on the chip (lower left) plays only a secondary role. (National Semiconductor)

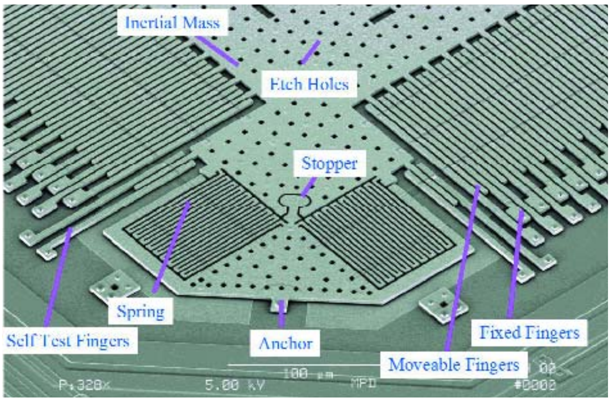

Figure 3. Motion-sensitive comb structures in the ADXL202 micromechanical acceleration sensor. (Analog Devices)

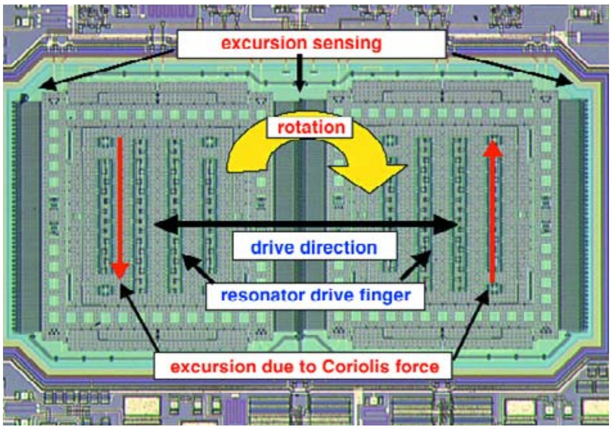

Figure 4. In the ADXRS150 rotational rate sensor, the paths of vibrating mechanical structures are altered when the device is rotated. (Analog Devices)

In this case, processing the measurement signal is especially difficult. The signal voltage from the Hall element is extremely small, and it is superimposed on a large offset voltage. In addition, both voltages are highly temperature dependent. Temperature compensation requires complex circuitry, and optimum results can only be achieved using a switching technique, similar to a chopper amplifier.

With these sensors, users can configure a whole range of parameters according to their wishes: sensitivity, the upper and lower limits of the measurement range, measurement bandwidth and the amount of temperature compensation. A special feature here is that the temperature dependence can either be entirely eliminated (even including its nonlinearity, for which purpose a quadratic correction network in included), or a certain proportion of the temperature dependence can be intentionally retained. This can be useful if (for instance) the sensor is used with a magnet that has its own temperature dependence. In this way, the temperature dependence of the overall system (and thus the temperature dependence of the switching distance, for example) can be reduced to nearly zero.

In normal measurement operation, this sensor is operated from a 5-V supply voltage and generates an analogue signal that is proportional to the local magnetic flux density. It can be programmed by increasing the supply voltage to a higher level and modulating the voltage. A voltage in the range of 5.6–6 V corresponds to a logic Low level, while the range of 6.8–8.5 V corresponds to a High level. The data are written serially. In this mode the sensor output operates digitally, and the internally stored parameter values can be requested and read out serially via the output. The sensor is electronically ‘sealed’ on conclusion of the programming process, and subsequent programming is no longer possible. The output signal is again analogue after programming.

This approach allows the number of leads to be kept to an absolute minimum: ground, supply voltage and output. This keeps down the cost, which essentially depends on the package type used and thus the number of leads. The packaged

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sensor, with dimensions of 4 × 4 × 1.5 mm, looks like a plastic-cased transistor. Its block diagram is shown in **Figure 1.**

Bus connection

In systems with many sensors, it is economical to connect all of them to the computer via a common bus, rather than using individual cabling. This means that each sensor must have a bus coupler, which in many cases can also be housed on the chip. An early example of this type of component was the National Semiconductor LM75, which had a delta/sigma A/D converter and an I^2C bus interface on the same chip. A large demand for ICs of this type quickly arose, so new types were continuously developed and their range of functions was constantly enlarged to meet the wishes of users. They ultimately evolved into complex monitoring components, which (for example) can be used in PCs to monitor not only the temperature but also a whole range of other quantities, such as fan speeds. **Figure 2** shows the block diagram of the LM87, which has so many functions that it has become a general-purpose ‘early warning system’ for all possible types of faults. Here the actual temperature sensor (at the bottom left) is only one of a host of elements.

MEMS

Now that we have learned how to accurately produce mechanical structures with micrometre dimensions, it’s possible to integrate sensor elements that operate using moving parts, such as sensors for pressure, force, acceleration, and rotational motion. Where we previously encountered metallic or ceramic parts with dimensions in the millimetre or centimetre range, we now find miniature structures made from monocrystalline silicon, which together with their associated electronics form a monolithic block. This combination of micromechanics and microelectronics forms a micro-electro-mechanical system (MEMS).

The first products of this type to be manufactured in large volumes were acceleration sensors for triggering air bags in cars. They contain two interleaved comb structures made from silicon, with one of them being firmly attached and the other being suspended such that it can move. Capacitances in the femtofarad range (1 femtofarad = 10^{-15} F) are created between these two structures. When the sensor is subjected to a mechanical impact, the movable comb is slightly displaced due to its inertial mass. This causes one capacitance to become larger and the other one to become smaller, which is sensed using an electronic bridge circuit. Such sensors have proved to be extremely reliable, and more than 100 million pieces have been produced by now. Some of them are even sensitive in two directions, such as the Analog Devices ADXL202 illustrated in **Figure 3** (www.analog.com).

Airbags in cars have already saved many lives, but electronic stabilisation systems can make an even greater contribution. They sense the rate of rotation of the vehicle about its vertical axis as the primary variable, and if it exceeds the maximum permissible value (as occurs with a skid), they initiate suitable steering and braking manoeuvres. In the event of rotation about the longitudinal axis (rollover), the airbags must inflate immediately.

Sensors for use in cars must be produced in large quantities at low costs. The glass-fibre gyroscopes used in avionics and space flight systems would be unaffordable. Here again components containing movable micromechanical structures have proven to be quite suitable, and they are already being produced by many manufacturers. They are based on the physical phenomenon of the Coriolis force: if a mass in a rotating system is displaced linearly in a radial direction, it experiences a deflection in the tangential direction. In the Analog Devices ADXRS150, a flexibly suspended mass is excited into resonant vibration by electrostatic forces, with an amplitude of ±3.5 µm and a frequency of approximately 15 kHz. If the chip is subjected to rotation, a force perpendicular to the direction of oscillation is exerted on the vibrating element, and in a manner similar to the previously described acceleration sensor, this causes a change in the capacitance measured between two interleaved comb electrodes.

In its practical implementation, the IC uses two sensor cells whose masses oscillate in antiphase. Not only does this neutralise the external vibration of the IC, it also makes it less sensitive to disturbance from vehicle vibration. **Figure 4** shows a portion of the chip, which measures only 3 × 3 mm. It is housed in a BGA package with dimensions of 7 × 7 × 3 mm.

Modular construction

Despite its considerable success, there is a problem with microsystem technology, which is that the large front-end development costs can only be recovered if the components are produced in large quantities. This is difficult to achieve for small and medium-sized sensor manufacturers.

One solution to this problem is to construct the sensors in modular form using several independent functional blocks, which can then easily achieve large production volumes. A concept employing three modules, which has been developed by AMA Fachverband für Sensorik e. V. (www.ama-sensorik.de) in close cooperation with industry, is shown in **Figure 5**. It consists of the following modules: 1) the measurement module with the sensor element and signal conditioning, 2) a microcontroller for additional signal processing (includ-

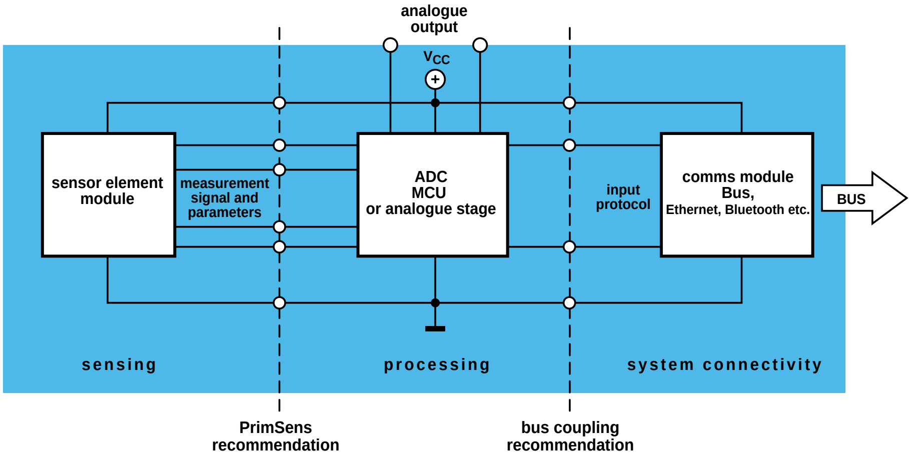

Figure 5. A modular microsensor technique using defined interfaces (PrimSens and Buscoupler).(AMA Fachverband für Sensorik e. V.)

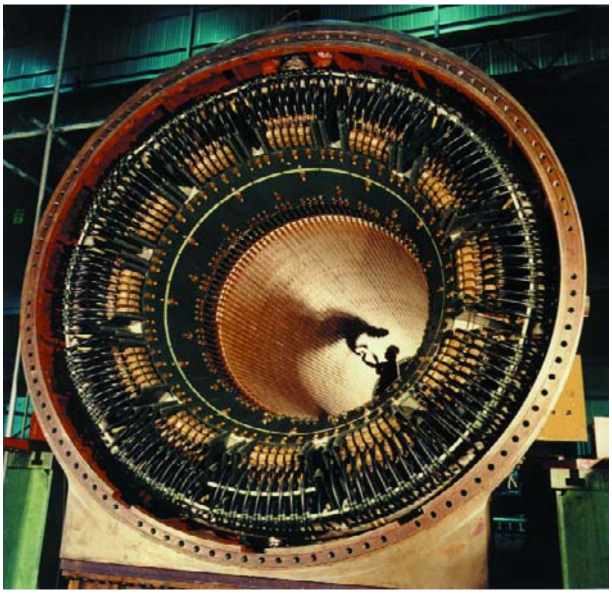

Figure 6. Temperature measurement using fibre-optic sensors inside a 1300-MW generator with extremely high electrical and magnetic field strengths. (Photo: Siemens)

ing digitising), and 3) a bus coupler if necessary. The modules are separated by two standardised interfaces. The first interface is called 'PrimSens', and the second is called 'Buscoupler'. The first products of this type were shown recently at the Hanover Fair.

Another modular concept defines a component system with small, square circuit boards with dimensions of 10 × 10 to 45 × 45 mm, which can be stacked on top of each other (www.match-x.org).

Interference-free measurement without electricity

The sensors we have examined up this point are all 'normal' sensors that work with electrical cables, but there are some places where it is not possible to run such cables, such as where there is an explosion hazard or where there is a risk of voltage discharge in a high-voltage installation – or in environments where there are strong electromagnetic fields, such as in radio transmitters or electrical generators.

In such situation, a different approach must be taken. A highly promising technique is optical measurement using light instead of electricity. The light is conveyed by a glass or plastic optical fibre to the measurement location, where it is affected by the quantity to be measured and then returned via the same optical fibre or a second fibre. The evaluation instrument determines the measurement value from the returning light. An example is the Lumitherm instrument made by the US company Ipitek, which transmits light pulses from an LED through a fibre to a measurement probe, where they excite luminescence in a fluorescent material. The duration of the luminescence depends on the temperature, and this effect is exploited to make measurements using the luminescent light returned to the instrument. Systems of this sort, in which the fibre only acts to convey the light, are called 'extrinsic' fibre-optic systems.

However, it is also possible to use the actual fibre as the measuring element. Such 'intrinsic' fibre-optic systems exploit the miniscule but still present effects of external physical quantities on the propagation of light through the fibre. If the wave nature of the light is also taken into account, very high sensitivity and resolution can be achieved. A widely used technique involves writing a 'Bragg grating' into the fibre. A Bragg grat-

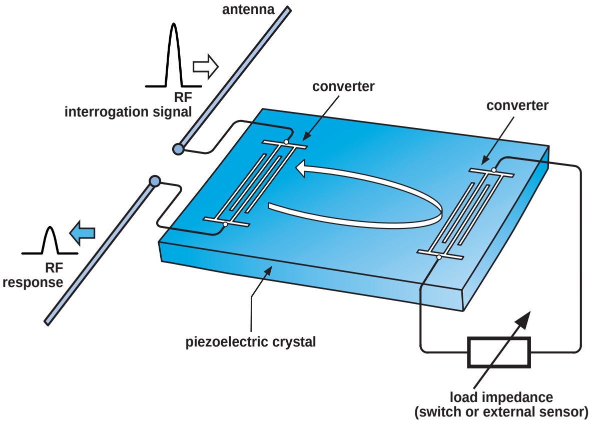

Figure 7. A wireless sensor using surface acoustic waves. The response signal is affected by the attached sensor element.

ing is a periodic series of regions having an elevated refractive index, which is generated by means of UV irradiation. Light with a wavelength that exactly corresponds to twice the grating spacing is reflected back to the optical source, while all other wavelengths pass through unaffected. If the fibre is stretched, light with a somewhat longer wavelength will be reflected, and this can be measured optically. This yields a highly sensitive elongation sensor that operates without electricity, cannot be affected by extremely strong ambient electromagnetic fields, and cannot itself interfere with anything else. There are very many physical effects that can influence the propagation of light in a fibre. Quantities that can be measured in this manner include elongation, tensile stress, vibration, flow, filling level, pressure, angle of rotation, temperature, ionising radiation and many others. This makes it possible to make a wide variety of measurements under difficult conditions, in situations where such measurements were previously considered to be out of the question – such as deep inside the 1300-MW generator shown in **Figure 6**.

Passive RF sensors

With rapidly rotating machine parts, a sensor link via commutator rings is frequently not sufficiently reliable. In such situations, it is possible to use another sensor technology that does not require a local power source: surface acoustic wave chips. These components, which are made from piezoelectric crystals (such as lithium niobate), are used as bandpass filters in radio receivers. An RF alternating voltage applied to the input comb electrodes (typically with a frequency of several hundred megahertz to a few gigahertz) generates a shallow mechanical wave on the surface of the crystal. This wave propagates over the length of the crystal until it is reflected at the other end and returns back to the electrodes, where it again generates an alternating voltage that is slightly delayed from the excitation pulse. If a sensor (for example, a capacitive pressure sensor) is connected to a second set of electrodes at the far end of the crystal, the reflection of the waves will be affected by the sensor in a manner that depends on the pressure. The pressure can then be determined by evaluating the returned signal (**Figure 7**). If an aerial is connected to the input, the sensor can be queried using radio waves. This technology has been studied in the research departments of tyre manufacturers as a means of acquiring measurement data from rotating tyres (pressure, temperature and traction) without using a battery as a power source. For more on this subject, see the article 'Wireless tyre-pressure monitoring' elsewhere in this issue.

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